

## INTRODUCTION

Watersheds of the Sacramento and San Joaquin River systems converge in an area known as the California Delta. As one of the world's most productive agricultural regions, the Delta is also an ecologically sensitive area with over 97,000 ha of farmland dissected by numerous waterways and separated by over 1,700 km of levees on 57 tracts or islands (Ingebritsen et al., 2000).

Prior to its conversion to agriculture, the Delta was the largest system of wetlands on the west coast of the United States. It consisted principally of tidal, freshwater emergent wetlands dissected by large tidal channels. Organic-rich Histosols began forming in the Delta about 4,000 years ago. By the mid-1800s, peat had accumulated to depths as much as 20 m in the central Delta with accretion rates ranging from 0.03 to 0.49 cm year<sup>-1</sup> (Whipple et al., 2012). The Delta was transformed into a productive agricultural area through drainage activities, levee building, and flood management beginning around 1848 (Weir, 1950; Thompson, 2006).

Since the onset of agriculture, much of the organic materials comprising the Delta's Histosols have disappeared, principally due to the oxidation of carbon (C) (Weir, 1950). As much as 8 m of subsidence have occurred in some areas (Whipple et al., 2012). Unustainable farming practices have led to the depletion of the soil resource as well as contributed to substantial quantities of carbon dioxide (CO<sub>2</sub>) released into the atmosphere.

A comprehensive inventory and update of soil survey map units in the Delta is underway and will enhance efforts to conserve the soil resources of this very important, yet environmentally vulnerable region. Documenting the amount of C is important to understand current composition of these soils, as well as the C flux. Organic soils in agricultural production contribute large quantities of greenhouse gas emissions, and management of these soils will be important not only for climate change, but also long term productivities of these important natural resources.

## Objective

To understand the quantities of C, as well as the form and distribution of organic and mineral materials with depth in soils mapped as the Rindge series. An evaluation of these concepts will allow for a better understanding of the impact of agricultural land use in this ecosystem.

## MATERIALS and METHODS

### Study Area

The soil survey area is within Major Land Resource Area (MLRA) 16 – California Delta, a small MLRA located southwest of Sacramento, California (Figure 1). It has a Mediterranean climate with a mean annual air temperature of 15 to 16°C and a mean annual precipitation ranging from 305 to 535 mm (USDA-NRCS, 2006). Map units selected for examination were located in San Joaquin and Sacramento Counties and composed of the Rindge series (Euic, thermic, Typic Haploaqualf).

### Field Methods

Four pedons representative of Rindge were described and sampled to > 200 cm. Descriptions and sampling methods were conducted according to typical soil survey procedures (Schoeneberger et al., 2012).

### Lab Methods

Analyses included particle size distribution, total C, and type of organic matter (rubbed/unrubbed fiber volume, Na pyrophosphate color) (Burt, 2014).

Determination of whether horizons were considered *organic versus mineral soil material* as defined in Keys to Soil Taxonomy (Soil Survey Staff, 2014) required evaluating both total C and total clay. The quantities of unrubbed fibers vs. rubbed fibers were significant in determining kinds of organic soil materials present: sapric, hemic, or fibric. Sodium pyrophosphate colors were also used as a means of analyzing the types of organic materials. Additionally, total organic matter (OM) along with the texture of the mineral fractions were used to determine the horizons' textures, or forms of OM in lieu of textures, as defined in Schoeneberger et al., 2012. Data were used to support horizon designations (Oa, Oe, A, etc.) for each pedon. Field descriptions and lab data allowed for revised horizon designations and taxonomic classifications of the "sampled as" pedons.



Figure 1. Location of the California Delta.



Figure 2. Pedon 13N3985. Sampled as Rindge. Correlated as fine, mixed, thermic, Histic Endoaqualf.



Figure 3. Landscape of sub-sea level Rindge muck, partially drained, 0 to 2 percent slopes, near Pedon 13N3985, looking down from levee.



Figure 4. Pedon 13N3991. Sampled as Rindge. Correlated as euic, thermic, Fluvaquentic Haploaqualf.



Figure 5. A large ditch provides drainage for sub-sea level Rindge soils. Pumps lift water from these ditches into the nearby Delta river system.



Figure 6. Corn harvest near Pedon 13N3991. Thick clouds of dust are normal during harvest season. When dry, the lightweight, poorly aggregated muck soils are easily blown by wind.

## CONCLUSIONS

- Drainage and agricultural development of Histosols caused significant OM oxidation, resulting in subsidence of the landscape, changes in soil properties, and increased release of CO<sub>2</sub>(g).
- Types of soil materials (organic, mineral) in these Histosols were directly impacted by management practices. Soils have been drained for agricultural land use, resulting in higher mineral concentrations and sapric OM near the soil surface. Less decomposed OM and higher amounts of fibers increased with depth. In more depleted soils, contact with the underlying mineral horizons is shallower.
- High quantities of mineral materials resulted in the recorelation of some pedons to Mollisols and should be considered in soil survey updates of these map units.
- Evidence indicates that C oxidation, soil loss, and landscape subsidence as a result of OM degradation processes will continue unless management practices change. Establishment of permanent easements and wetland restoration projects would reverse these processes.
- Wetland restoration projects would allow these Histosols to once again become C sinks and be one means of counteracting global climate change.

## REFERENCES

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## RESULTS and DISCUSSION

The initial focus of this soil survey project was the evaluation of map units comprised predominantly of Histosols, soils in this area that are most vulnerable to oxidation and subsidence as well as wind erosion. The Rindge series represents the greatest extent of Delta Histosols (23,900 ha), and is mapped in areas of very deep organic materials.

Clay percentage (Tables 1 to 4) varied widely between pedons as well as varied irregularly with depth. Across all pedons, clay ranged from 11 to 71%. Within pedons, clay was variable. For example, it ranged from 41 to 55% in pedon 13N3986 (Table 1) and from 22 to 71% in pedon 13N3991 (Table 3).

Variability of total C with depth was likely influenced by both the depositional environment and subsequent weathering (oxidation of OM) associated with anthropogenic land use. Total C ranged from 11 to 24% in the upper 50 cm of these soils, and generally increased with depth in the lower horizons. Maximum total C ranged up to 47% in the Oi2 horizon (91 to 125 cm) of pedon 13N3991 (Table 3). These data show a trend that OM is less oxidized in lower horizons of each pedon.

The exception to these trends was in pedon 13N3985 (Table 4) with a maximum total C in the uppermost (Oap) horizon (17.8%), and C decreasing with depth. The lack of total C in the lower horizons of this pedon may be due to the environment at the time of alluvial deposition in this delta ecosystem. Encountering these horizons in a Rindge pedon also suggested that historically thick deposits of organic materials have oxidized, resulting in shallower depths to low-C mineral horizons (2Cg1, 2Cg2, and 2Cg3).

Compared to upper horizons, greater rubbed and unrubbed fiber volume in lower organic horizons suggested that the OM is better preserved with depth in these soils. For example, the upper horizons of pedon 13N3986 (Table 1) had unrubbed fiber volume ranging from 4 to 12 and lower horizons had volumes ranging from 16 to 64. This is the result of oxidation of OM near the surface where the soil was drained and tilled for agricultural land use.

Fiber content was also used to determine the types of organic materials present. There seemed to be good correlations of pyrophosphate extract colors to percentage of fibers and field designations of Oa and A horizons (Tables 1 to 4). Correlations in hemic and fibric materials were not as good. Oe horizons (Table 1) had 10YR 6/3 extract colors, indicating hemic organic material. However, the rubbed fiber content ranged from 14 to 16%, below the minimum fiber requirement of 17%. A rerun of lab analyses may be considered for fiber volume for these Oe horizons, since field determinations and extract colors seemed to be consistent with hemic materials.

Oi horizons (Table 3) had a pyrophosphate extract color of 10YR7/3, a Munsell color near the grouping for fibric materials, but just outside the designated range. Quantities of unrubbed and rubbed fibers from lab analysis again seemed to be inconsistent with field descriptions, as well as pyrophosphate extract colors. Minimum unrubbed and rubbed quantities were much lower than expected for the Oi horizons, with rubbed fiber contents of 16%, 20%, and 8%, in order of depth. These values overlap values for sapric and hemic materials, and therefore are inconsistent with both field determinations and pyrophosphate extract colors. Comparisons of these data elements, overall OM content, and corresponding horizon designations are shown in the tables.

Over time, the classifications of these human-altered soils mapped in the Delta have changed, and will continue to change, given the documented rates of OM oxidation and subsidence (Weir, 1950). Organic matter oxidation over the past 150 years of agricultural land use has resulted in the concentration of mineral material in upper soil horizons as evidenced in these four pedons. Additionally, the depths to mineral horizons below organic soil materials is becoming less and less as the landscape subsides. These facts are evident in the morphologies and classifications of the four "sampled as" Rindge soils. Rindge classifies as a Typic Haploaqualf, and in many cases depths to underlying mineral horizons are greater than 2 m. However, only one of the four pedons, 91P0766 (Table 2), retained the Histosol classification after evaluation of lab data. While this pedon still classified as Rindge, evidence of change is present as exhibited by the concentration of mineral material in the upper 25 cm, resulting in a mucky clay loam surface texture. This pedon also has mineral horizons with very little C starting at a depth of 180 cm.

Two other pedons, 13N3986 (Table 1) and 13N3985 (Table 4, Figure 2, and Figure 3), classified as Histic Endoaqualf. In each pedon, the required depths of organic soil material to classify as Histosols were not met, although pedon 13N3986 was very close.

Pedon 13N3991 (Table 3, Figures 4 to 6) classified as a Fluvaquentic Haploaqualf due to the presence of a thin A horizon mid-profile. This pedon also had mineral horizons starting at 143 cm, only 13 cm below the bottom of the control section. The thinness of the organic materials is evidence of significant carbon loss on a landscape that once had several meters of organic accumulation.

Table 1. Pedon 13N3986 | S2012CA067002 | Map unit: Rindge mucky silt loam, partially drained, 0 to 2 percent slopes Sampled as Rindge: Euic, thermic Typic Haploaqualf Revised to Correlated as: fine, mixed, thermic Histic Endoaqualf

Depths (cm)	Horizon Designation (field)	Horizon Designation (recorrelated)	Clay Percentage of Mineral Fraction (% by wt)	Total Carbon (TC)** (% by wt)	Fibers Unrubbed/ Rubbed (% by vol)	Na Pyro Color (Munsell)	OM Content (% by wt)	Horizon Texture or Form of OM in Lieu of Texture
0-7	Oap1	Ap1	54.3	15.0	10/2	10YR 4/3	26	mk-sic
7-18	Oap2	Ap2	54.3	15.7	12/2	10YR 4/3	27	mk-sic
18-30	Oap3	Ap3	53.8	15.5	4/1	10YR 4/3	27	mk-sic
30-40	Oap4	Ap4	51.4	16.2	6/2	10YR 4/3	28	mk-sic
40-62	Oa1	Oa1	50.3	18.7	---	---	---	pt
62-84	Oa2	Oa2	55.3	17.6	---	---	---	pt
84-110	Oa3	Oa3	41.7	27.4	64/20	10YR 5/4	47	muck
110-150	Oe1	Oe1	---	20.3	30/16	10YR 6/3	35	mk-pt
150-190	Oe2	Oe2	---	24.9	40/14	10YR 6/3	43	mk-pt
190-225	Oe3	Oe3	---	18.6	40/16	10YR 6/3	32	mk-pt
225-265	Cg	Cg	---	12.6	16/4	10YR 6/3	22	---
265-280	C	C	41.4	7.2	---	---	12	---

\*\* Green values indicate insufficient carbon to qualify as organic soil material.

Table 2. Pedon 91P0766 | 91CA077001 | Map unit: Kingile muck, partially drained, 0 to 2 percent slopes Sampled as Rindge: Euic, thermic Typic Haploaqualf Correlated as Rindge: euic, thermic Typic Haploaqualf

Depths (cm)	Horizon Designation (field)	Horizon Designation (recorrelated)	Clay Percentage of Mineral Fraction (% by wt)	Total Carbon (TC)** (% by wt)	Fibers Unrubbed/ Rubbed (% by vol)	Na Pyro Color (Munsell)	OM Content (% by wt)	Horizon Texture or Form of OM in Lieu of Texture
0-5	Oap1	Ap1	29.3	12.9	---	---	22	mk-cl
5-25	Oap2	Ap2	27.6	11.4	---	---	20	mk-cl
25-58	Oa1	Oa1	32.3	16.9	---	---	29	mk
58-94	Oa2	Oa2	34.7	23.4	---	---	40	mk
94-122	Oa3	Oa3	35.6	24.0	---	---	41	mk
122-180	Oa4	Oa4	26.4	25.8	---	---	44	mk
180-225	2C1	2C1	14.2	0.5	---	---	1	l
225-250	2C2	2C2	10.5	0.2	---	---	0	sl

\*\* Green values indicate insufficient carbon to qualify as organic soil material.

Table 3. Pedon 13N3991 | S2012CA077005 | Map unit: Rindge muck, partially drained, 0 to 2 percent slopes Sampled as Rindge: Euic, thermic Typic Haploaqualf Revised to Correlated as: euic, thermic Fluvaquentic Haploaqualf

Depths (cm)	Horizon Designation (field)	Horizon Designation (recorrelated)	Clay Percentage of Mineral Fraction (% by wt)	Total Carbon (TC)** (% by wt)	Fibers Unrubbed/ Rubbed (% by vol)	Na Pyro Color (Munsell)	OM Content (% by wt)	Horizon Texture or Form of OM in Lieu of Texture
0-9	Oap1	Oap1	40	22.9	24/10	10YR 4/4	39	mk
9-25	Oap2	Oap2	45.5	23.8	16/4	10YR 3/4	41	mk
25-42	Oap3	Oap3	45.1	22.8	16/4	10YR 4/3	39	mk
42-70	Oa	A	71.4	12.5	---	---	22	mk-cl
70-97	Oi1	Oi1	---	36.0	20/16	10YR 7/3	62	pt
97-125	Oi2	Oi2	---	47.1	48/20	10YR 7/3	81	pt
125-143	Oi3	Oi3	---	26.6	28/8	10YR 7/3	46	pt
143-173	2Cg1	2Cg1	59.5	2.7	---	---	---	c
173-220	2Cg2	2Cg2	21.9	0.4	---	---	---	l

\*\* Green values indicate insufficient carbon to qualify as organic soil material.

Table 4. Pedon 13N3985 | S2012CA067001 | Map unit: Rindge muck, partially drained, 0 to 2 percent slopes Sampled as Rindge: Euic, thermic Typic Haploaqualf Revised to Correlated as: fine, mixed, thermic Histic Endoaqualf

Depths (cm)	Horizon Designation (field)	Horizon Designation (recorrelated)	Clay Percentage of Mineral Fraction (% by wt)	Total Carbon (TC)** (% by wt)	Fibers Unrubbed/ Rubbed (% by vol)	Na Pyro Color (Munsell)	OM Content (% by wt)	Horizon Texture or Form of OM in Lieu of Texture
0-12	Oap1	Oap	50.5	17.8	12/2	10YR 4/3	31	mk
12-26	Oap2	Ap	57.4	17.2	4/1	10YR 4/3	30	mk-sic
26-49	Oa1	Oa	52.1	17.7	8/2	10YR 4/3	31	mk
49-65	Oa2	A1	45.2	15.7	12/2	10YR 4/3	27	mk-sic
65-84	Oa3	A2	52.8	10.5	---	---	18	mk-sic
84-112	Oa4	A3	43.2	7.7	---	---	13	mk-sic
112-140	Cg1	2Cg1	20	0.5	---	---	1	sl
140-195	Cg2	2Cg2	15.3	0.5	---	---	1	fsl
195-215	Cg3	2Cg3	12.5	0.5	---	---	1	fsl

\*\* Green values indicate insufficient carbon to qualify as organic soil material.